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Synthetic aperture processing of wideband scattering measurements made in the DRDC Atlantic acoustic calibration tank

John Fawcett
Richard Fleming

Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2008-112
September 2008

Canada

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Abstract

In this experiment we placed various objects, including actual practice limpet mines, on a one-metre diameter disc which was suspended in the DRDC Atlantic acoustic calibration tank from a rotator pole. Two different discs were considered, one aluminum and the other fibreglass. These discs were then rotated under a fixed MMPP projector and hydrophone. The geometry was arranged so that the mineshapes would appear directly under the projector/hydrophone during the rotation. The time series data and the corresponding spectra were presented and used for detection and classification experiments in another DRDC Atlantic technical memorandum. In the time series of that report, the echoes scattered from objects were evident when the projector and receiver were at significant distances away from the object. This was due to the wide beamwidths of the projector and hydrophone. In this report, we investigate the improved spatial resolution which can be obtained by beamforming the time series. There was only a single hydrophone used as a receiver so that the array for the beamforming is constructed using the motion of the disc with respect to the hydrophone. Examples of the scattered time series before and after beamforming will be presented.

Résumé

Dans la présente expérience, nous avons placé divers objets, y compris des mines ventouses d'entraînement réelles, sur un disque de un mètre de diamètre qui était suspendu dans le bassin d'étalonnage acoustique de RDDC Atlantique à l'aide d'une perche rotative. Deux disques ont été examinés : un en aluminium et l'autre en fibre de verre. Ces disques ont été tournés sous un projecteur à tube multimode (MMPP) et un hydrophone fixes. La géométrie a été configurée de sorte que les formes des mines paraissaient directement sous le projecteur/l'hydrophone durant la rotation. Les données sur les séries chronologiques et les spectres correspondants ont été présentées et ont servi dans le cadre des expériences de détection et de classification d'un autre document technique de RDDC Atlantique. Dans les séries chronologiques présentées dans ce document, les échos diffusés par les objets étaient détectables lorsque le projecteur et le récepteur étaient placés à une grande distance de l'objet. Les grandes largeurs de faisceau produites par le projecteur et l'hydrophone avaient causé ce problème. Dans le présent rapport, nous examinons la résolution spatiale améliorée qui peut être obtenue par la conformation de faisceau aux fins des séries chronologiques. À cet effet, un hydrophone unique a été utilisé comme récepteur en vue d'élaborer le réseau pour la conformation de faisceau à partir du mouvement du disque par rapport à l'hydrophone. Des exemples de séries chronologiques diffusées avant et après la conformation de faisceau sont présentés.

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Executive summary

Synthetic aperture processing of wideband scattering measurements made in the DRDC Atlantic acoustic calibration tank:

J. Fawcett; R. Fleming; DRDC Atlantic TM 2008-112; Defence R&D Canada – Atlantic; September 2008.

Introduction or background: The sonar detection of small mines (or other objects) placed upon a reflective surface such as a ship's hull or a wharf piling is a challenging problem. In another report, we showed that the echo from a wideband acoustic projector could be used to successfully detect the scattering from limpet mines with respect to background echoes. The sonar pulse could also penetrate into objects and echo features could be used for classification. In that experiment, there was only a single fixed receiver. The objects were rotated on a disc below the receiver. If instead, we consider the disc as fixed, then the receiver and projector pair is rotating with respect to the disc. Thus, by coherently summing across the sonar time history, one can construct a synthetic aperture and beamform the time series. The resulting beamformed series should have an improved spatial resolution and signal-to-noise ratio.

Results: It is shown that wideband echo time series at a single receiver can be beamformed. The resulting sonar image has better spatial resolution and some scattering features are enhanced with respect to the background echoes.

Significance: This experiment indicates the potential of using synthetic aperture processing with a simple wideband projector/receiver system. The relatively poor spatial resolution of the single receiver system can be improved by using a synthetic aperture technique. Although a rotational geometry was used in the experiment described in this report, one can also construct synthetic apertures for translational motions.

Future plans: We would like to perform trials with the projector/hydrophone system on a remotely-operated vehicle (ROV) with mine-like objects deployed on the surface of a ship or pier. In this case, the synthetic aperture would correspond to the along-track motion of the sonar.

Sommaire

Traitement d’ouverture synthétique des mesures de diffusion large bande effectuées dans le bassin d’étalonnage acoustique de RDDC Atlantique

J. Fawcett; R. Fleming; DRDC Atlantic TM 2008-112; R & D pour la défense Canada – Atlantique; Septembre 2008.

Introduction ou contexte: La détection par sonar de petites mines ou d’autres objets placés sur une surface réfléchissante, comme la coque d’un navire ou un pilotis de quai, constitue un problème difficile. Dans un autre rapport, nous avons montré que l’écho produit par un projecteur acoustique à large bande permettait de détecter la diffusion causée par les mines ventouses par rapport aux échos d’arrière-plan. Les impulsions du sonar pouvaient aussi pénétrer dans les objets, et les caractéristiques des échos pouvaient servir à la classification. Dans le cadre de cette expérience, il y avait un récepteur unique fixe. Les objets étaient tournés sur un disque situé sous le récepteur. Par contre, si nous considérons que le disque est fixe, c’est le groupe récepteur-projecteur qui tourne par rapport au disque. Par conséquent, en additionnant de façon cohérente l’ensemble de l’historique temporel du sonar, on peut construire une ouverture synthétique et conformer le faisceau aux fins des séries chronologiques. Les séries chronologiques avec conformation de faisceau ainsi créées devraient avoir une résolution spatiale et un rapport signal/bruit améliorés.

Résultats: Les résultats montrent que les séries chronologiques d’échos à large bande détectées par un récepteur unique permettent la mise en forme d’un faisceau. L’image sonar ainsi obtenue possède une meilleure résolution spatiale, et certaines caractéristiques de diffusion sont améliorées en ce qui a trait aux échos d’arrière-plan.

Importance: Cette expérience montre qu’il est possible d’utiliser le traitement d’ouverture synthétique avec un système simple de projecteur/récepteur à large bande. On peut améliorer la résolution spatiale relativement faible d’un système à récepteur unique en utilisant une technique d’ouverture synthétique. Bien qu’une géométrie rotationnelle ait été utilisée dans le cadre de l’expérience décrite dans le présent rapport, on peut aussi construire des ouvertures synthétiques pour les mouvements de translation.

Perspectives: Nous aimerions effectuer des essais à l’aide du système de projecteur/d’hydrophone sur l’engin télécommandé (ROV) et d’objets analogues à des mines posées sur la surface d’un navire ou d’une jetée. À cet effet, l’ouverture synthétique correspondrait au mouvement longitudinal du sonar.

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1 Introduction

The detection of mines or explosive devices planted on a ship's hull or on a piling is currently a research topic of much interest. High frequency sonars may provide a rough image of the area of interest or a bathymetric sonar may be able to resolve the height difference caused by an object placed on a surface. However, on the basis of geometric measurements alone, it is anticipated that there is potential for many false alarms. In previous reports [1-2] it was shown that it is possible to reliably distinguish echoes of interest from background echoes in the case of a wideband incident pulse. In this experiment, a single fixed projector/receiver pair was used and a sequence of sonar pings, as the disc rotated, was recorded. These basic time series and the FFT spectra of the objects of this report, including realistic limpet mineshapes were described in detail and used in [2] for detection and classification studies. Although these mineshapes were realistic in shape, their internal composition is not indicative of an actual limpet mine. Due to the beamwidths of the projector and hydrophone, the echoes from the various scattering objects could be observed for several pings before and after the object was directly below the projector and hydrophone. This suggests that by coherently summing along the hypothesized time/space trajectories (i.e., time-domain beamforming) we should be able to improve the along-track spatial resolution of the system. In this case, there is not a receiver array, but the array is synthetically constructed by considering the different relative positions of the projector/hydrophone as the disc is rotated. The concepts of constructing a synthetic aperture have been widely studied with traditional synthetic aperture sidescan sonars [3]. Also, the estimation of the reflectivity map from a series of echo measurements is related to tomographic inversion methods with simple time-domain beamforming corresponding to the backprojection operation [4].

In the experiment we used a small High Frequency Multi-Mode Pipe Projector (HF MMPP) which is capable of yielding a very wideband pulse with significant power. The projector that is used has been described in previous reports [5-6]. For this experiment, 3 actual limpet mineshapes were borrowed from Fleet Diving Unit Atlantic (FDU-A) and were affixed to circular discs of either aluminum or fibreglass. These 1-m diameter discs were then attached to a rotator pole which allowed the disc to be rotated below the projector/hydrophone at a constant speed. As well, some other targets were considered. In particular, we constructed 3 identically-shaped, small minelike objects differing only in their interior fill. This process was done for both types of discs, at 2 projector offsets, and for various types of incident pulses. Other rotations were done in a bistatic projector/hydrophone mode. In total, 34 rotations were carried out.

The straightforward beamforming method we use is described and then representative data from the various rotations will be presented in the original and beamformed temporal domains.

2 Experimental setup and targets

The experimental system that was used was discussed in detail in [1]. In Figures 1-6 below we show some pictures of the setup and some of the targets that are discussed in the section on beamforming. In the examples presented in this report we will consider the following targets: (a) a polymer-bodied practice limpet-mine shape (with and without an additional small object on the top) (b) a right-cylindrical practice mineshape (c) a small tungsten carbide sphere (d) an aluminum disc (e) a hemispherical practice mineshape and (f) three small puck-shaped objects with different interior fills.

Figure 1 The first HF MMPP and hydrophone configuration used during the rotations

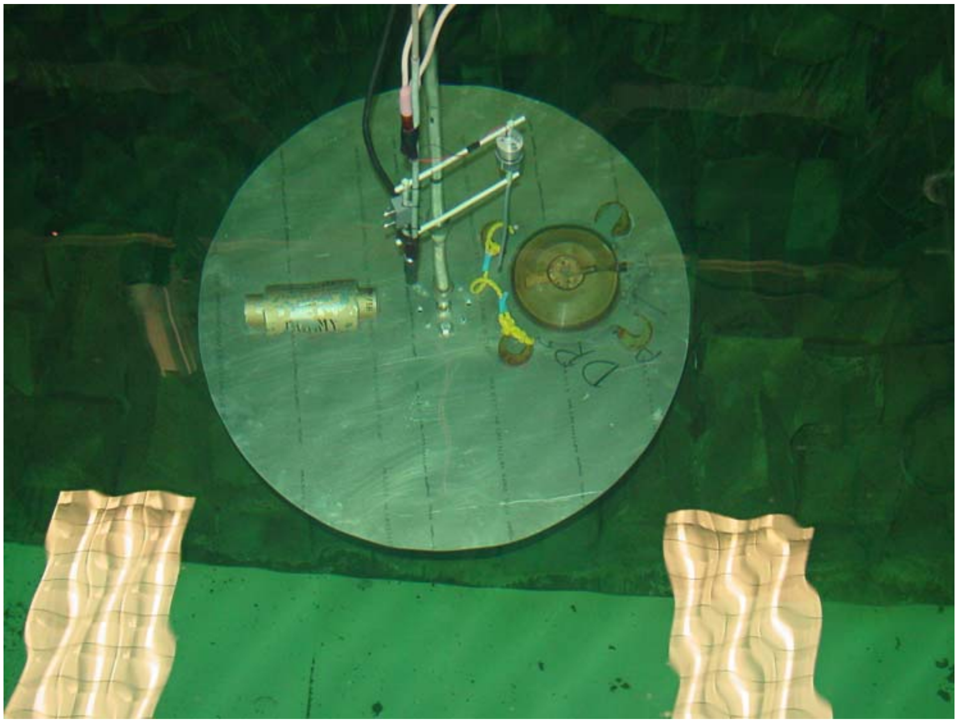

Figure 2 Looking down on disc from above - in this case, a bistatic HF MMPP/hydrophone configuration was used. The polymer-bodied and right-cylindrical practice limpet mines can be seen.

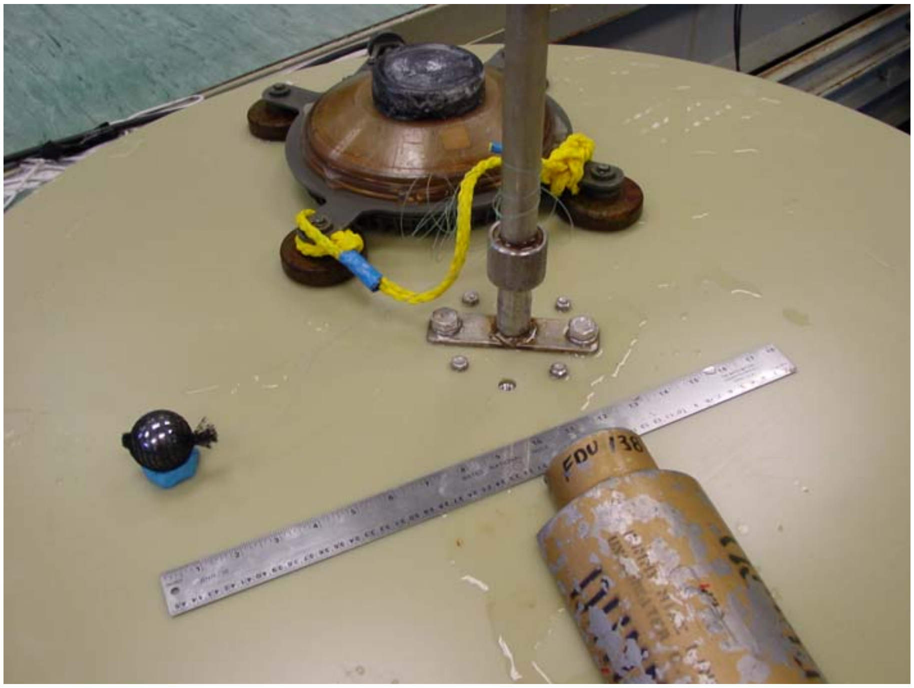

Figure 3 The polymer-bodied and right-cylindrical limpet mineshapes with the small tungsten carbide sphere between them. The polymer body has an additional small object on the top.

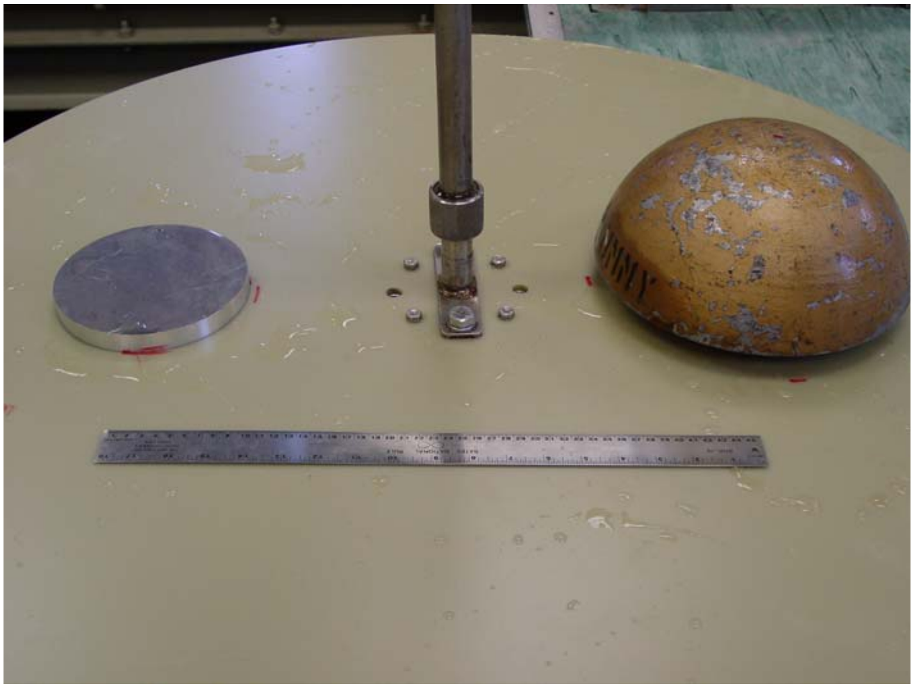

Figure 4 The hemispherical mineshape and aluminum disc.

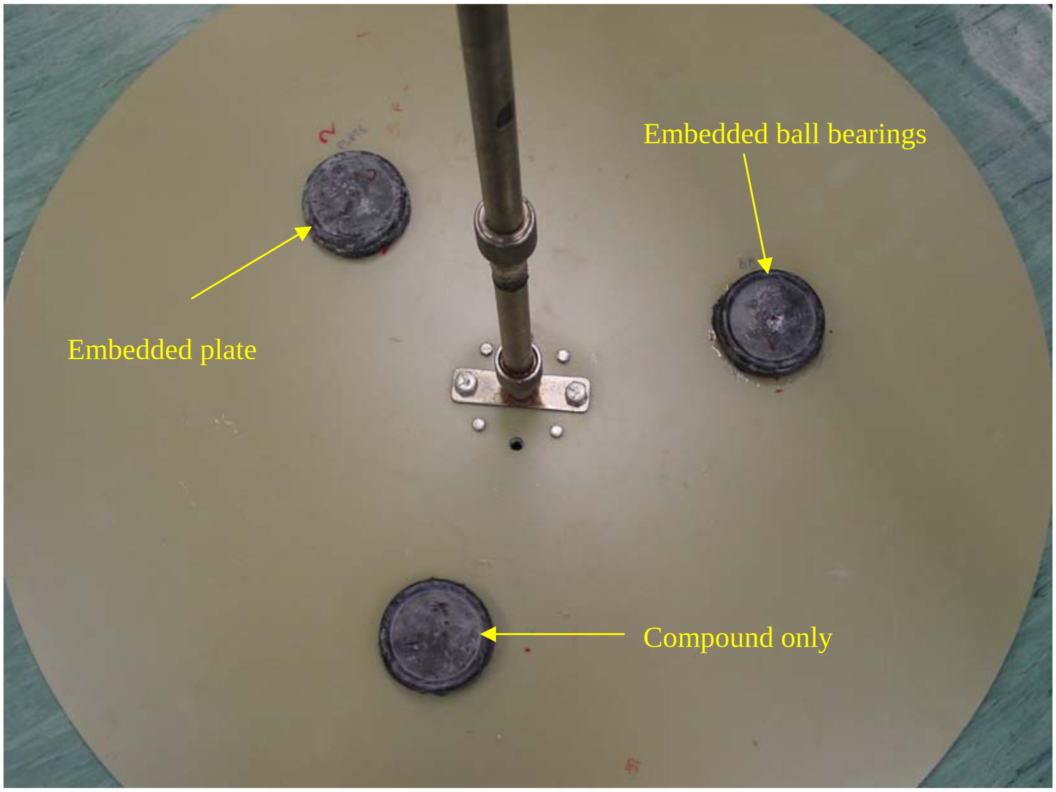

Figure 5 Three identical mineshapes with different interior fills.

3 Beamforming algorithm

In this section we describe the basic formulae that we use for the beamforming process. We will take the scattering objects to lie on the horizontal (i.e., at a fixed depth) circle $r = r_0$. For the case of the projector and hydrophone aligned with each other, they will lie on the circle $r = r_0$, $z=z_p$ and $r = r_0$, $z=0$ respectively. In the case of the bistatic alignment, the projector will lie on the circle $r_1 = r_0 - \delta$, $z=0$ and the hydrophone on the circle $r_2 = r_0 + \delta$, $z=0$. We will consider 2 time variables: p_i refers to the ping index and τ refers to the time within the echo of a given ping. Let us consider in Cartesian coordinates, a fixed point scatterer at (x_t, y_t, z_t). Then the travel time, $T(x_t, y_t, z_t)$, for the ping from the projector (x_p, y_p, z_p) to reach this point and scatter back to the hydrophone (x_h, y_h, z_h) is given by

$$T = (\sqrt{(x_t - x_p)^2 + (y_t - y_p)^2 + (z_t - z_p)^2} + \sqrt{(x_t - x_h)^2 + (y_t - y_h)^2 + (z_t - z_h)^2})/1500. \quad (1)$$

For the inline alignment, we can consider $(x_t, y_t) = r_0 (\cos \phi_t, \sin \phi_t)$, $(x_p, y_p) = (x_h, y_h) = r_0 (\cos \phi(p_i), \sin \phi(p_i))$. Here we are considering the scatterer as fixed and the projector/hydrophone rotating with respect to it. Then we can write for Eq.(1)

$$T(p_i) = (\sqrt{2r_0^2(1-\cos(\phi_t - \phi(p_i)) + (z_t - z_p(p_i))^2} + \sqrt{2r_0^2(1-\cos(\phi_t - \phi(p_i)) + (z_t - z_h(p_i))^2})/1500 \quad (2)$$

Note in Eq.(2) that we consider the altitudes of the projector and hydrophone to be variable with respect to the ping index. As we shall see in the examples, the depth to the ensonified portion of the disc does vary somewhat during a rotation. We will consider the depth of the plate to be constant (corresponding to the depth at the first ping) and the altitude of the projector/receiver to vary. For the bistatic arrangement the travel time $T(p_i)$ can also be simply expressed in terms of r_1, r_2 and $\phi(p_i)$.

$$T(p_i) = \frac{\sqrt{r_0^2 + r_1^2 - 2r_0 r_1 \cos(\phi_t - \phi(p_i)) + (z_t - z_p(p_i))^2} + \sqrt{r_0^2 + r_2^2 - 2r_0 r_2 \cos(\phi_t - \phi(p_i)) + (z_t - z_h(p_i))^2}}{1500} \quad (3)$$

The object's coordinates (ϕ_t, z_t) are defined in terms of the data's discrete indices. We will consider discrete indices of ϕ_τ corresponding to the same values of $\{\phi(p_i)\}$ varying from 0 (first ping) to 2π (last ping). Let us shift the time indices within each ping so that zero corresponds to the pulse from the projector passing the depth of the receiver. Then we will consider values of the depth coordinate $\{z_t\}$ of the plate corresponding to $j\ \Delta\tau\ 750$, $j=0,\ldots,N$. From Eq. (2) we will compute for a specified interval of angle indices, the appropriate time index. For negative values of angle and for values greater than 360° the angle index will wrap around. Along these paths, the recorded time series will be summed.

4 Experimental results

The incident pulses that are considered in this report are a [17 57] kHz compensated Sinc pulse, an uncompensated [8 90] kHz Sinc pulse, and for a few experiments, compensated [9 103] and [50 110] kHz pulses. The term “Sinc” denotes that the spectrum of the specified waveform to the projector is unity across the frequency band. However, due to the Transfer Function of the projector, the spectrum of the output pulse in the water will not be flat. A compensated pulse signifies that the waveform input to the HF MMPP projector is chosen so that the output spectrum from the projector is unity across the band [a b] kHz. The method for specifying an input waveform to produce a specified output spectrum is described in Ref.5. For the uncompensated pulse, the input waveform had a flat spectrum in the band [8 90] kHz and we simply used the resulting output pulse as the incident pulse. We tried to construct a compensated version of this pulse but the result seemed to produce very poor results when used for scattering from the plate. The reasons for this are not clear – perhaps there were some non-linear effects in causing either the hydrophone or plate to vibrate. Later in the experiments, the projector/receiver setup was changed. In this configuration, it was possible to use higher frequency wideband compensated pulses and we used [9 103] and [50 110] kHz compensated pulses. Overall, using the two types of plates, different sets of objects, different MMPP and receiver configurations, and different incident pulses, we carried out 34 rotations.

For the first example of the rotation time series and beamformed data we consider a compensated [17 57] kHz pulse. The polymer-bodied and small cylindrical mineshapes of Figs.2 and 3 were on the fibreglass disc. The shapes and the projector/hydrophone were at a nominal radius of 0.25m with respect to the centre of the disc. In Fig.6a we show the initial ping/time series history, in Fig.6b the time series after a shifting of the pings to “flatten” the echo from the disc, and in Fig.6c the beamformed time series. The time series in Fig.6b has also been interpolated (spline interpolation) to produce a time series with a time increment of ¼ the original sampling. The “flattening” of the disc echo was accomplished by manually selecting a few (5) time shifts (in addition to zero shifts for the first and last ping indices) and then using spline interpolation to produce a continuous shift index for each ping. Each ping was re-sampled to correspond to these shifted time indices. One could estimate the time shifts automatically by using cross-correlations between pings and the first ping. This proved successful in the case that the disc echo was dominant in the time series. However, this method fails for pings where the presence of the object significantly shadows or changes the disc echo. Thus in this and following examples, we simply use a manual selection of 5 shift points, followed by interpolation. Figure 6c shows the beamformed result. The objects have become better defined in terms of their lateral extent and the beamforming seems to accentuate some internal scattering features.

In this beamforming we used 1201 points (600 points on either side of each hypothesized scattering point). The beamforming consists of summing the time series along the hypothesized paths in the time/ping space. We apply a cosine-taper weighting to the points along the path away from the centre point. In Fig.7 we show some of the tracks used for summation superimposed upon the time-shifted data space. It can be seen that part of the paths appear on the last pings: this corresponds to the paths going into negative angles and appearing wrapped-around at the later angles. We can also beamform for the slightly bistatic arrangement which was used in the experiments. The resulting beamformed image is shown in Fig.8. The results are similar to those for the inline configuration although some of the internal features seen in Fig.6 are not evident.

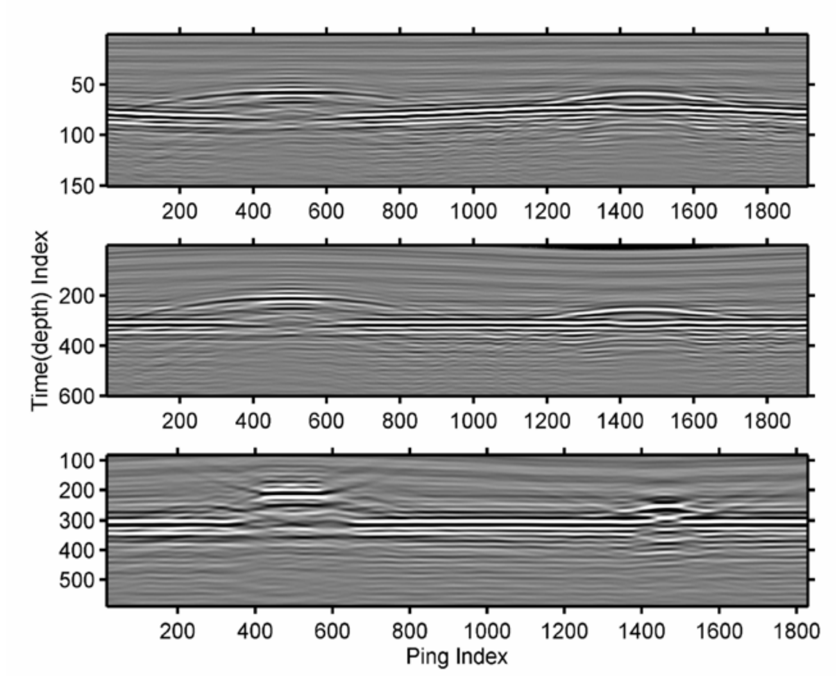

Figure 6. (Top) The portion of the original ping/time series with the target/disc echos(middle) the ping/time series after shifting and interpolation (bottom) the beamformed image

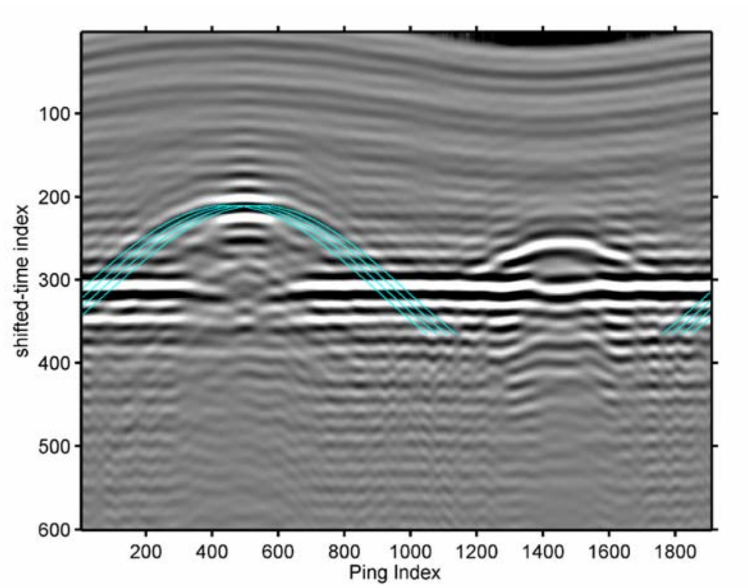

Figure 7 The time-shifted and interpolated data of the previous figure with some sample integration lines shown in cyan

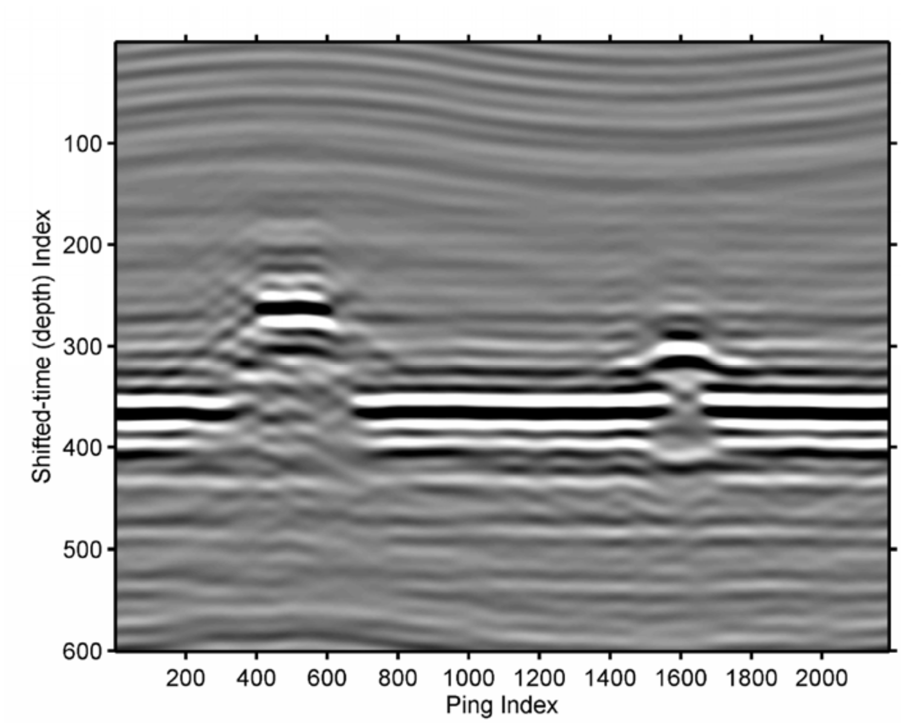

Figure 8 Beamformed image [17 57] kHz compensated pulse- bistatic configuration.

In the following examples, we will only consider the inline configuration, although there were 2 different configurations of this type used during the experiment (these are discussed in more detail in Ref.2).

In the next example, there were 3 targets placed upon the fibreglass disc (fig.3): the polymer-bodied mineshape as before but with a smaller mineshape filled with an epoxy on top and the aluminum cylindrical shape. In between these 2 targets, a small Tungsten-Carbide sphere was placed. The 2 big targets are easily seen in the time series data (Fig.9a). Four hundred points (801 point, total) were used for the summation path on either side of the hypothesized locations. The beamformed image, shows a fairly complicated structure for the augmented polymer-mineshape. The cylindrical mine shape in this case does not have the appearance of "ringing" as it did in Fig.6. The reason for this is not clear, except that after redeploying the disc with the new targets, perhaps the projector/receiver/targets geometry had changed a little. It is interesting to note that after the beamforming that the small sphere is weakly observable (indicated by an arrow in Fig.9b). This is emphasized in the lower panel, where the difference of the image in the ping-index direction is shown.

The next example that we consider utilized the second arrangement for the projector/hydrophone. In this case it was possible to obtain a compensated [9 103] kHz pulse. The first target is a small disc of solid aluminum and the second target is the hemispherical dummy mineshape. The scattering from the small disc can be directly seen in the timeseries. The scattering form the

hemispherical shape is also directly observed but is rather diffuse and extends over a large angular range. The beamformed image is much more “focussed’ for both objects.

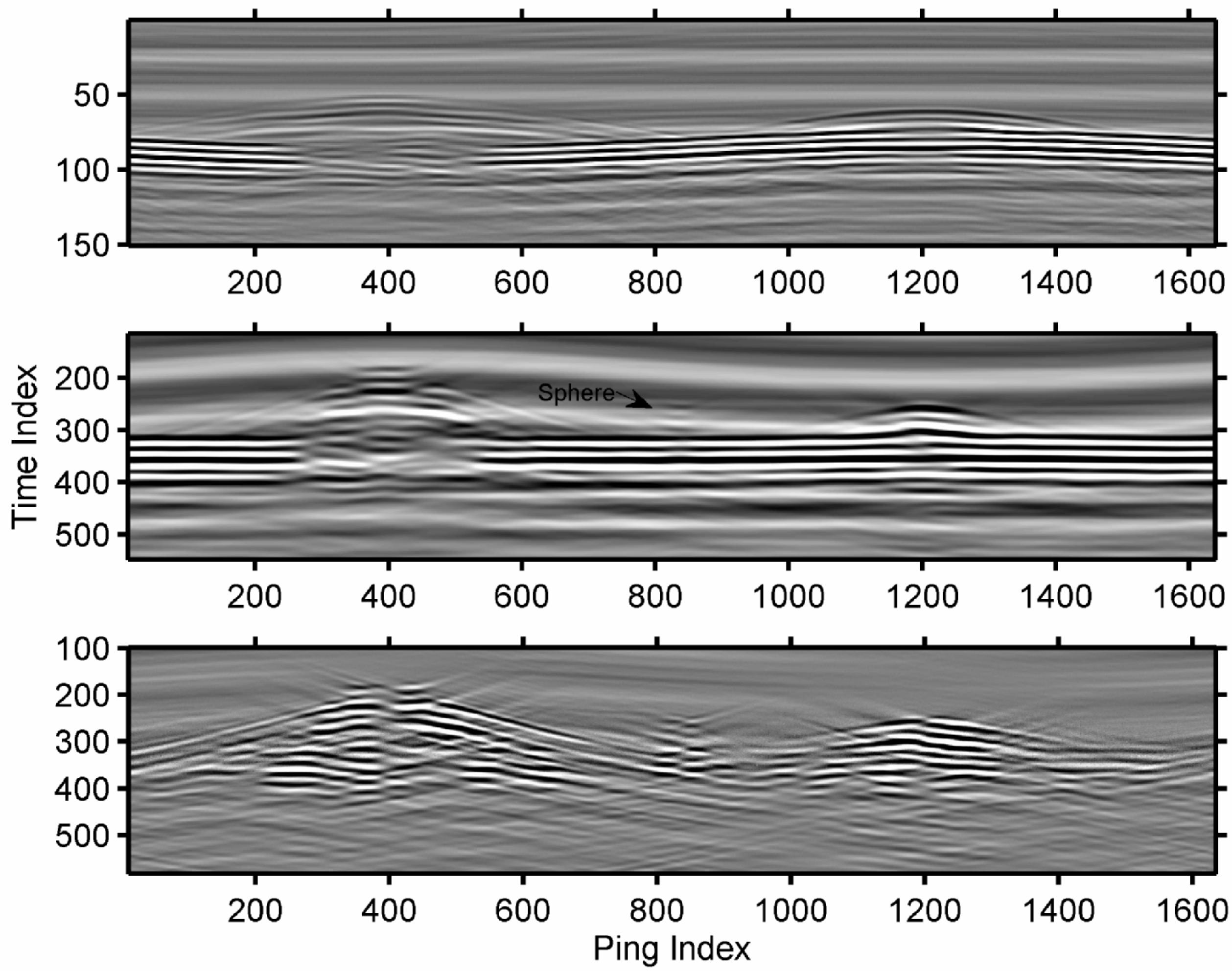

Figure 9 (Top) Original time series, (middle beamformed image and (bottom) differenced beamformed image The data was an uncompensated [8 90] kHz pulse. The 3objects on the fibreglass disc are the plastic mine with an absorbing mineshape on the top, a small tungsten carbide sphere and the small aluminum cylinder shape. The difference image shown in the last plot is the result of applying the difference operator in the Ping Index direction.

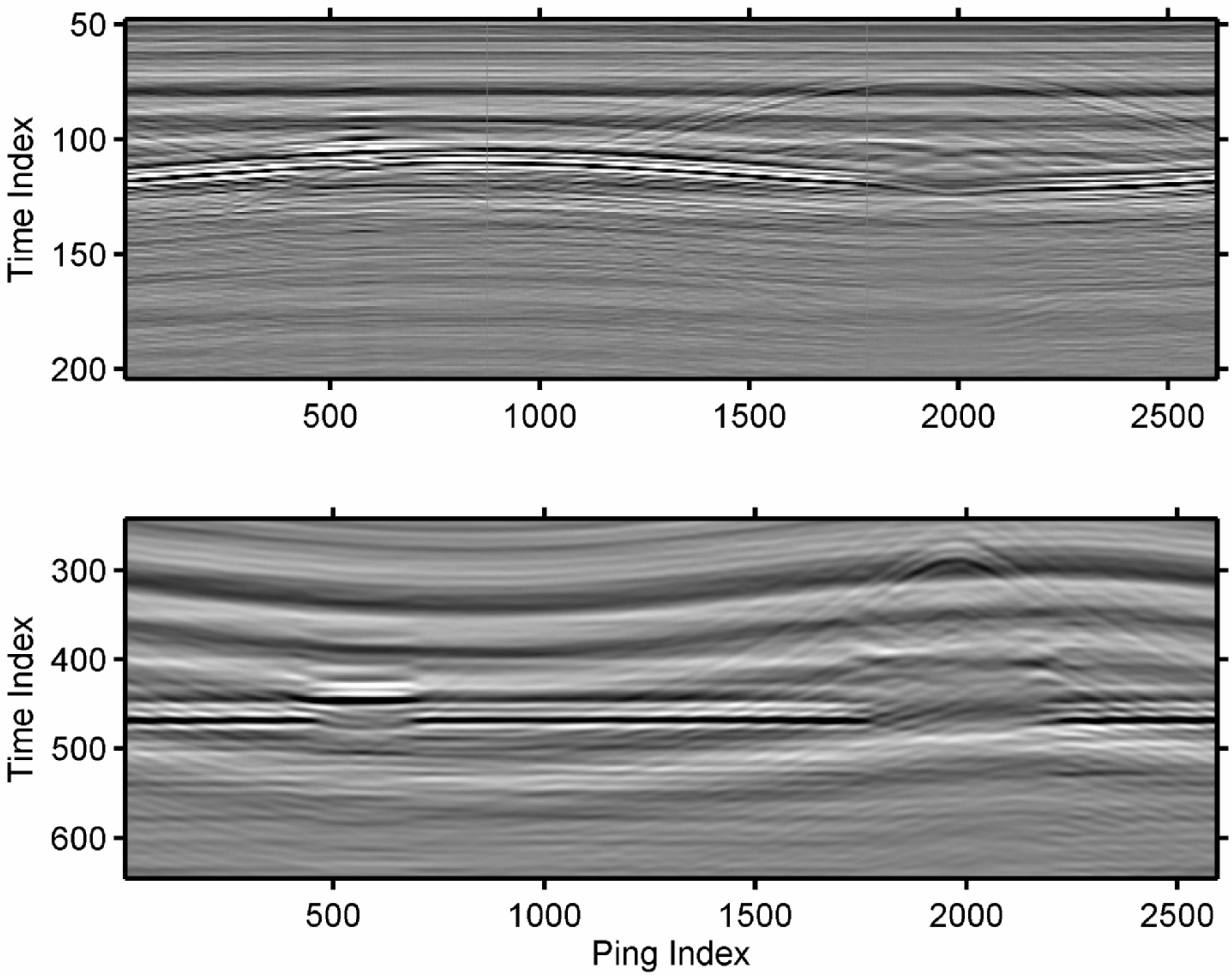

Figure 10 Timeseries (top) and beamformed (bottom) image of aluminum disc and large hemispherical shape on fibreglass disc. This is for the second projector/hydrophone arrangement and the [9 103] KHz pulse.

For a final example of beamforming, Fig.11, we consider the fibreglass disc with 3 identical small discs filled with an epoxy material. These 3 discs differ only with respect to their interior structure. The first one contains a small aluminum disc surrounded by the epoxy. The second disc encountered during the rotation was filled with just the epoxy and the third disc contained an epoxy/steel ballbearing mixture. These objects, particularly the first and third discs are observable in the timeseries record. However, their extent and their scattering features (particularly for the first and third disc) are clearer in the beamformed image. In this case 800 points (1601) were used for the beamforming summation – the number of pings was 3129 in this case.

Thus far, we have compensated for the varying depth to the disc by manually selecting 7 ping offsets (including the first and last ping) and then using a spline fit to determine a smooth offset curve. These refer to the data after the data has been upsampled by a factor of 4. One can automatically determine this offset curve by using, for example, the cross-correlation of a ping with respect to the first ping. Alternatively, one can cross-correlate successive pings to determine the small shift between pings and then integrate this to obtain the offset curve. The dominant feature for most of the pings is the reflection off the disc; however, for the larger targets, this layer reflection is obscured and the additional reflection way from the layer is observed. This can cause large jumps in the estimated time (depth) shifts to the disc. For this particular rotation, however, the targets are quite small, and so they do not interfere much with the cross-correlation process. In Fig.12 below we show the curve as determined using the peak (followed by a quadratic interpolation about the peak of the cross-correlation) as well as the shifts that we specified after a visual inspection. Two slight anomalies in the cross-correlation curve, corresponding to two of the targets, can be observed.

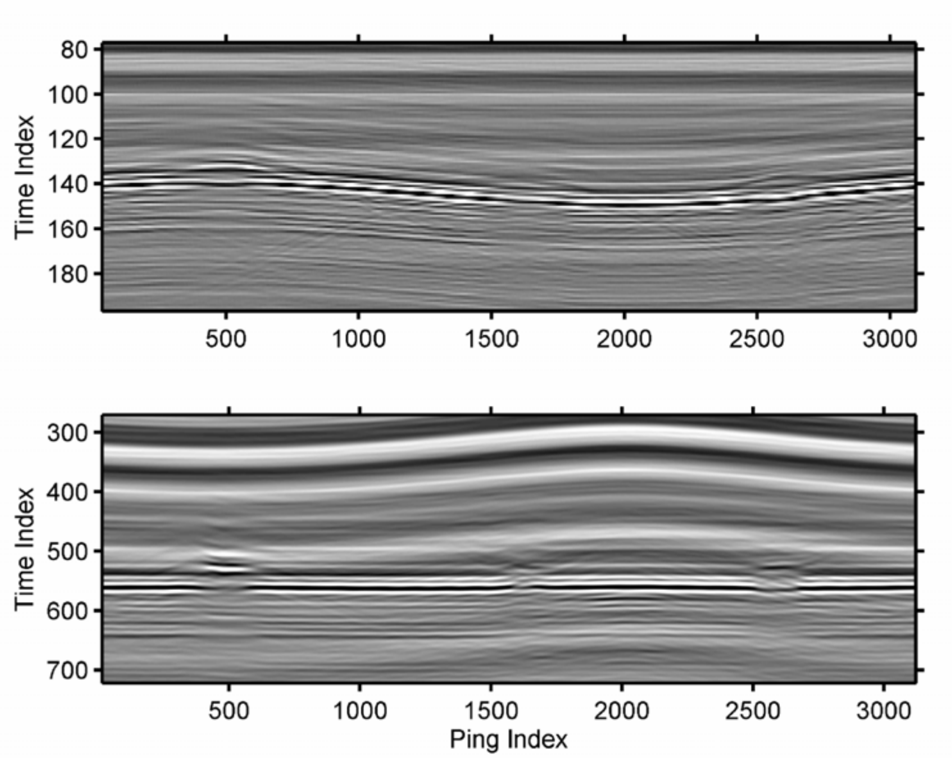

Figure 11 Rotation time series (top) and beamformed image (bottom) for 3 identical small targets with different fill. The pulse was the [9 103] kHz pulse.

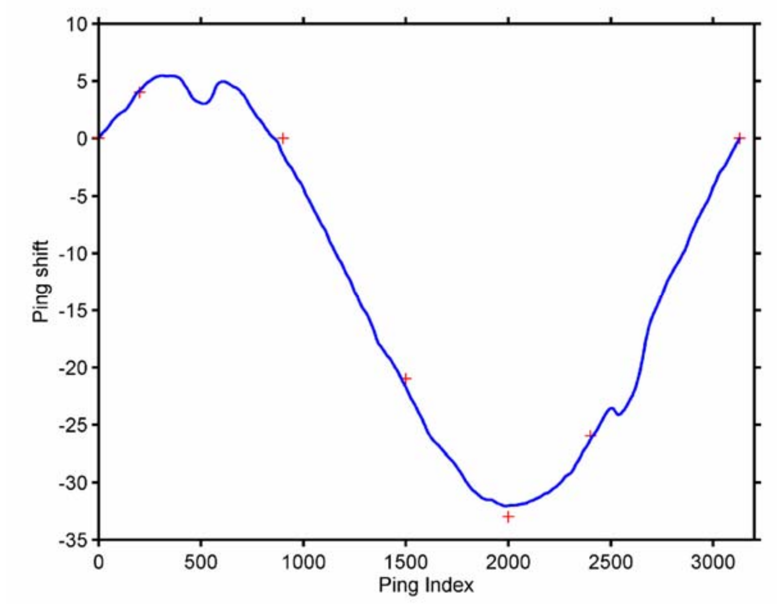

Figure 12 The estimated ping shifts using the cross-correlation method (blue) and manually supplied values (red +).

5 Summary and discussion of results

We have shown in this report that the time series from a single projector/hydrophone system can be beamformed using the rotation of the disc to generate the array, or considering the disc as fixed the motion of the projector/hydrophone. This experiment indicates the potential of using synthetic aperture processing with a simple wideband projector/receiver system. The relatively poor spatial resolution of a single receiver system can be improved by using a synthetic aperture technique. Although a rotational geometry was used in the experiment described in this report, one can also construct synthetic apertures for translational motions. In the future we would like to perform trials with the projector/hydrophone system on a remotely-operated vehicle (ROV) with mine-like objects deployed on the surface of a ship or pier.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development
MMPP	Multi-mode pipe projector
HF MMPP	High frequency multi-mode pipe projector
ACB	Acoustic calibration barge
kHz	kilohertz
RHIB	Rigid hull inflatable boat

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In this experiment we placed various objects, including actual practice limpet mines, on a one-metre diameter disc which was suspended in the DRDC Atlantic acoustic calibration tank from a rotator pole. Two different discs were considered, one aluminum and the other fibreglass. These discs were then rotated under a fixed MMPP projector and hydrophone. The geometry was arranged so that the mineshapes would appear directly under the projector/hydrophone during the rotation. The time series data and the corresponding spectra were presented and used for detection and classification experiments in another DRDC Atlantic technical memorandum. In this report, we consider the beamforming of the time series. There was only a single hydrophone used as a receiver so that the array for the beamforming is constructed using the motion of the disc with respect to the hydrophone. Examples of the scattered time series before and after beamforming will be presented.

Dans la présente expérience, nous avons placé divers objets, y compris des mines ventouses d'entraînement réelles, sur un disque de un mètre de diamètre qui était suspendu dans le bassin d'étalonnage acoustique de RDDC Atlantique à l'aide d'une perche rotative. Deux disques ont été examinés : un en aluminium et l'autre en fibre de verre. Ces disques ont été tournés sous un projecteur à tube multimode (MMPP) et un hydrophone fixes. La géométrie a été configurée de sorte que les formes des mines paraissaient directement sous le projecteur/l'hydrophone durant la rotation. Les données sur les séries chronologiques et les spectres correspondants ont été présentées et ont servi dans le cadre des expériences de détection et de classification d'un autre document technique de RDDC Atlantique. Dans les séries chronologiques présentées dans ce document, les échos diffusés par les objets étaient détectables lorsque le projecteur et le récepteur étaient placés à une grande distance de l'objet. Les grandes largeurs de faisceau produites par le projecteur et l'hydrophone avaient causé ce problème. Dans le présent rapport, nous examinons la résolution spatiale améliorée qui peut être obtenue par la conformation de faisceau aux fins des séries chronologiques. À cet effet, un hydrophone unique a été utilisé comme récepteur en vue d'élaborer le réseau pour la conformation de faisceau à partir du mouvement du disque par rapport à l'hydrophone. Des exemples de séries chronologiques diffusées avant et après la conformation de faisceau sont présentés.

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MMPP, mine detection, broadband

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